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WATER TRANSPORT and the ENERGY ABSORBED BY HEATED LODGEPOLE PINE BRANCH TIPS

BY

Warren B Cohen, Philip N. Omi, and Merrill R. Kaufmann

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ACKNOWLEDGEMENTS

This research was supported by the Intermountain Research Station of the USDA Forest Service, the Jet Propulsion Laboratory through the National Aeronautics and Space Administration's Graduate Student Researchers Program, and with McIntire-Stennis funds distributed through the College of Forestry and Natural Resources at Colorado State University. The authors would like to thank Ronald A. Susott, Richard C. Rothermel, and E. Raymond Hunt, Jr. for their thoughtful reviews of the manuscript, Hariharan K. Iyer for his guidance on statistical matters, Michael Ryan for his timely advice at the early stages of this work, and Debbie Wright-Olson and Joseph Stevens for their assistance in the field.

Submitted: Forest Science
29 Nov 88

WATER TRANSPORT AND THE ENERGY ABSORBED BY HEATED LODGEPOLE PINE BRANCH TIPS

ABSTRACT[1]

Initial water content of foliated branches is known to greatly influence the spread of fire into and through the crowns of live trees. However, nondrought-stressed trees may transport additional water to foliated branches when heated. To investigate this hypothesis, we compare energy absorbed by similar intact and detached branch tips of well-watered lodgepole pine trees (Pinus contorta Dougl. ex Loud.) during heating in a specially designed calorimeter. To reach and maintain 250 C for 3 minutes, intact branch tips absorbed 49 % more energy (primarily for water vaporization) than detached branch tips; an amount equivalent to 0.62 g of water per gram dry branch. After heating, no water remained in the detached branch tips and intact tips had a mean residual water content of 10.8 %. Nondrought-stressed lodgepole pine trees transport at least 20 times more water to their crowns when heated than when transpiring normally. Heating-related water transport delays the drying of crown fuels and may be highly significant in governing the spread of crown fire in lodgepole pine forests.

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[1] Key words: crown fire; forest fire; fire danger; live fuels; preheating.

INTRODUCTION

Wildland fires are classified according to the fuel stratum through which they principally spread. Those that spread through the canopies of live trees and shrubs are called crown fires. A lack of knowledge concerning basic mechanisms governing crown fire initiation and spread inhibits accurate assessment of crown fire hazard (Albini 1984, Alexander 1988). Accurate assessment is important because crown fires account for a disproportionately large share of the costs and damages associated with wildfires.

The initiation and spread of crown fires have been previously studied (Van Wagner 1973 and 1977, Haines 1982, Springer and Van Wagner 1984, Albini and Stocks 1986). Observations indicate that crown fires primarily happen during periods of low branch and foliage water contents, and less frequently occur when water contents are high (Hough 1973, Van Wagner 1974, Fuglem and Murphy 1980). In experimental studies, Van Wagner (1963 and 1967) observed crown fires in severed Scots pine (Pinus sylvestris L.), white spruce (Picea glauca (Moench) Voss), and balsam fir (Abies balsamea (L.) Mill) Christmas trees. Trees with low water contents burned more readily and vigorously than those with high water contents. Van Wagner (1968) observed rates of crown fire spread through red pine (Pinus resinosa Ait.) in three separate prescribed fires. Van Wagner concluded that variations in tree crown water content accounted for spread rate differences. Quintilio (1977) demonstrated the dependence on water content of foliage mass loss during the combustion of severed lodgepole pine trees (Pinus contorta Dougl. ex Loud.).

Water content is the amount of water contained in branch tissue, expressed on a per gram dry weight basis. As such, it measures the amount of water initially contained in a branch prior to its heating. Initial water content is an important regulator of crown ignition susceptibilty and fire behavior because moisture must vaporize from crown fuels before ignition. However, initial water content may only account for a portion of the water vaporized from heated crown fuels.

Rothermel and Susott (in preparation) hypothesize that nondrought-stressed conifer trees forestall crown ignition by transporting water to heated foliated branches. In an earlier study, we placed severed lodgepole pine, Engelmann spruce (Picea engelmannii Parry ex Engelm.), and subalpine fir (Abies lasiocarpa (Hook.) Nutt.) branches in potometers and heated the branches to 225 C (Cohen and others 1988). Water vaporization rates were as much as 50 times greater from heated branches than from the same branches prior to heating. If water is transported to intact branches during heating, additional vaporization could strongly influence crown fire behavior.

Tree crowns absorb energy when heated. Most of the absorbed energy vaporizes water, while the remainder vaporizes other volatile compounds and raises branch temperature. Absorbed energy is calculated as:

$$E = \lambda * M_f + H_p, \qquad [1]$$

where E is the convective energy absorbed (J g^{-1} dry branch), λ is the latent heat of water vaporization (2550 J g^{-1} water), M_f

is the water content fraction (g water g^{-1} dry branch), and H_p is the heat of pyrolysis (400 J g^{-1} dry branch). This formulation is based on unpublished data for green lodgepole pine needles (R.A. Susott, personal communication) and on published data for green ponderosa pine needles (Pinus ponderosa Laws.) heated from 45 to 250 C (Susott 1982). A detached branch having 125 % water content heated to 250 C should absorb approximately 3588 J g^{-1} dry branch, 3188 of which is used to vaporize water (Equation 1).

In this study, we investigate heating-related water transport in nondrought-stressed lodgepole pine trees. Here, we compare the energy absorbed by intact and detached branch tips (branch terminal ends, 30 cm in length) heated in a specially designed tree branch calorimeter. If water is transported into a heated intact branch, then energy absorbed per gram dry branch tissue during an extended heating period should be greater than the amount absorbed by a similar, but detached, branch during an equivalent heating period.

METHODS

Our calorimeter's heating chamber is a steel cylinder 44 cm in length by 5 cm in diameter. The cylinder is surrounded by two layers of insulation and stovepipe. Heat is provided at the air inlet of the heating chamber by a Master model HG751B heat gun[2].

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[2] Mention of trade names does not imply product endorsement by the authors or the organizations they represent.

During heating, temperature at the chamber inlet is controlled by a Hewlett Packard HP71B computer. The computer was programmed to activate the heat gun for progressively larger fractions of time during a 3 second cycle. After running for approximately 1 minute to collect preheating energy data, the program heated the chamber inlet from ambient temperature to 250 C. Temperature was increased at a rate of 15 C min^{-1} for 16 minutes. Inlet temperature was held isothermally at 250 C for an additional 3 minutes. This 20 minute heating period was sufficient to vaporize all water initially contained in detached branch tips, without igniting them. A temperature of 250 C was the maximum practical for repeated use of the calorimeter, and the 15 C min^{-1} increase was the maximum repeatable heating rate. Via a Hewlett Packard HP3421A data acquisition system, thermocouples measure temperatures at the inlet and outlet ends of the heating chamber. Air flow through the chamber is measured from the pressure change in a venturi tube using a Type 590D Barocel pressure sensor (Dresser Industries, Inc.). Chamber inlet and outlet temperatures and air flow and temperature were sampled at 3 second intervals, or 400 times, during each 20 minute run. A gasoline generator provided the calorimeter with power.

Our study was conducted in August, 1987 in a subalpine forest at the U.S. Forest Service Fraser Experimental Forest near Fraser, Colorado. Air temperature at the study site ranges between -40 and 32 C, with frost possible any month of the year. Mean monthly temperatures are -10 and 13 C in January and July,

respectively. Annual precipitation averages 570 mm, most of which falls as snow. Moist environmental conditions prevailed thoughout the data collection period.

We selected 18 open-grown, vigorous trees (2-7 m in height) with accessible lateral branches about 1 m above ground. From each tree we selected a lateral branch that had several branch tips. From each lateral branch we chose a pair of similar tips for heating; one to remain intact, the other to be severed from the branch prior to heating. We determined the water content (g water g^{-1} dry branch) of three other tips from the same lateral branch. The amount of energy absorbed by branch tips is highly dependent on initial water content (Equation 1). Thus, we included in our data analysis only the 13 branch tip pairs associated with water content standard deviations of less than 10 % (Table 1).

The portion of each branch tip to be heated consisted of the terminal 13 cm of foliage and stem and 17 cm of adjacent stem. The 30 cm tip was placed inside a copper screen before its insertion into the heating chamber. The screen prevented contact between the foliage and the chamber wall. This minimized heat flow from the chamber wall to the cooler branch and maximized heat transfer from the hot air flowing past the branch.

After heating, we repeated the following procedure for each 30 cm branch tip:

(1) We weighed the branch tip and then further dried it in an oven for 10 minutes at 225 C.

(2) We reweighed the branch tip to determine its dry weight and the residual water content remaining after calorimeter heating.

(3) We calculated the rate of energy absorption every 3 seconds during the calorimeter run as:

$$E_b = m * C_p * (T_0 - T_i), \qquad [2]$$

where E_b is the rate of convective energy absorbed by the branch tip ($J\ s^{-1}$), m is the mass flow rate of air ($Kg\ s^{-1}$), C_p is the specific heat of air ($KJ\ Kg^{-1}\ {}^0K^{-1}$), T_0 is the chamber outlet temperature (^0K), and T_i is the chamber inlet temperature (^0K).

(4) We multiplied E_b by 3 s to obtain the amount of energy absorbed by the branch tip each 3 seconds.

(5) We standardized the data by dividing each 3 second amount by branch tip dry weight.

(6) We summed the standardized amounts over the 400 sample points to calculate standardized cumulative energy absorbed by the branch tip.

(7) From the cumulative data for the 13 branch tip pairs, we calculated differences in cumulative energy absorbed for each pair (absorption difference, intact minus detached) and the mean absorption difference over all 13 pairs. Naturally paired branch tips were chosen, permitting us to use paired difference t-tests (Mendenhall 1975) on the 13 absorption differences at all 400 sample points.

The calorimeter absorbs some of the heat passing through its heating chamber, causing an inflated energy measurement. Twenty blank runs indicated that mean energy loss was between 15 and 20 % of the mean total energy measured when branch tips were heated. For graphic illustration, we wanted to more accurately depict actual energy absorbed by branch tips during heating than our analysis thus far permitted. To accomplish this, we subtracted the mean amount of energy loss at all 400 sampling intervals from the energy absorption data obtained in step (4) above, before proceeding to steps (5) and (6). After step (6), we calculated mean blank-corrected cumulative energy absorption separately for intact and detached branch tips.

RESULTS

The mean difference in cumulative energy absorbed by branch tip pairs is shown in Figure 1. The absorption difference was positive even before the onset of heating at minute 1 (30 C), and rapidly increased after heating began. At minute 8 (135 C), the absorption difference was near 500 J g^{-1} dry branch. High data variability is associated with the short-term leveling of the difference between minutes 8 and 10 (165 C). At minute 20 (250 C), the absorption difference was 1573 J g^{-1} dry branch. The difference is highly significant ($p < .025$) throughout the 20 minute calorimeter run.

Blank-corrected calorimeter data are shown in Figure 2. Detached branch tips absorbed energy at a steady rate from the

start of the calorimeter run until minute 4 (75 C). Between minutes 4 and 5 (90 C) the rate of energy absorption increased, reaching a maximum between minutes 5 and 9 (150 C). The rate of energy absorption between minutes 9 and 17 (250 C) was approximately equal to the rate at the start of the run. By minute 17, energy absorption by detached branch tips ceased.

Intact branch tips absorbed energy differently than detached tips. Most apparent, is the greater rate of energy absorption exhibited throughout the calorimeter run. As with detached branch tips, the rate of energy absorption by intact tips slowed by minute 9. But in contrast to detached branch tips, the absorption rate beginning at minute 9 (approximately 3 J g^{-1} dry branch s^{-1}) lasted throughout the remainder of the heating period. By the end of the calorimeter run, intact branch tips absorbed an average of 49 % more energy than detached branch tips. Mean residual water contents of detached and intact branch tips were 0.0 and 10.8 %, respectively (Table 1).

An average of 3208 J g^{-1} dry branch were absorbed by detached branch tips during the 20 minute calorimeter run (Figure 2). Overall mean water content of branch tips prior to heating was 120.8 % (Table 1). The energy absorbed by detached branch tips is in close agreement with the amount expected for branches at 120.8 % water content (3480 J g^{-1} dry branch, Equation 1). Thus, the calorimeter underestimated energy absorbed by the branch tips during heating by an average of less than 10 % when data were corrected for blank run energy losses.

DISCUSSION

Equation 1 states that the amount of energy absorbed by branch tips is proportional to the amount of water vaporized from them. The positive and statistically significant mean difference in cumulative energy absorption throughout the calorimeter run (Figure 1) indicates more water was vaporized from intact, than from detached, branch tips. The positive absorption difference before heating began can be explained by water transport theory. When plants (or plant branches) experience severe water stress (such as by detachment) leaf water potential decreases. This triggers a closure of stomata and a reduction in water loss (Jarvis 1980, Kramer 1983, Fiscus and others 1983).

By minute 17, energy absorbed by detached branch tips had leveled off (Figure 2), indicating all water initially contained within them had vaporized. In contrast, energy absorbed by intact branch tips did not level off, but continued at a steady rate of 3 J g^{-1} dry branch s^{-1} until the end of the heating period. This implies water was transported into intact branch tips at a steady rate, even when foliage temperature was 250 C. Residual water contents of 0.0 and 10.8 %, respectively, for detached and intact branch tips (Table 1) confirms that water was transported into intact tips. An absorption difference of 1573 J g^{-1} dry branch at the end of heating, is equivalent to 0.62 g more water per gram dry branch (1573 J g^{-1} branch / λ, as defined in Equation 1) vaporized from intact, than from detached, branch tips. Clearly, nondrought-stressed lodgepole pine trees

transport significant amounts of water to their foliated branches when heated.

During heating of the branch tips to 250 C, pyrolysis accounted for a loss of branch dry weight. The loss was probably less than 10 % for the detached branch tips (extrapolated from Susott 1982). Because intact branch tips remained cooler throughout the heating period, they probably lost a smaller percentage of their initial dry weight than the detached tips. If so, when the energy data were standardized, actual absorption differences were underestimated.

Under normal field conditions, lodgepole pine foliage absorbs around 0.003 J cm^{-2} s^{-1} for transpiration. This is calculated by:

$$E_f = TFD * \lambda, \qquad [3]$$

where E_f is the rate of convective energy absorbed by the foliage (J cm^{-2} s^{-1}), TFD is the transpiration flux density (1 μg cm^{-2} s^{-1}; extrapolated from Running 1980 and Kaufmann 1982); and λ is as defined in Equation 1. During calorimeter heating, the rate of energy absorbed by intact branch tips reached a steady rate of 3 J g^{-1} dry branch s^{-1}. Assuming that foliage is the principal vehicle for water vaporization from a heated branch, it is the foliage that absorbed most of the heat energy incident upon the branch. For branch tips used in this study, average foliage dry weight was 2.54 g and branch dry weight (foliage plus stem) was 4.95 g. This is equivalent to 1.95 g dry branch g^{-1} dry foliage.

Thus, the rate of energy absorbed by the foliage during heating was 5.85 J g^{-1} dry foliage s^{-1} (3 J g^{-1} dry branch s^{-1} * 1.95 g dry branch g^{-1} dry foliage). Lodgepole pine foliage has a surface area of approximately 95 cm^2 g^{-1} dry weight (Kaufmann and Troendle 1981). Therefore, 0.06 J cm^{-2} of foliage s^{-1} were absorbed by intact branch tips to vaporize water at the steady rate attained. This implies that water transport during heating was 20 times the rate associated with normal transpiration (0.06 J cm^{-2} s^{-1} / 0.003 J cm^{-2} s^{-1}). Thus, heating-related water transport appears sufficient to inhibit crown fuel drying, and therefore delay or prevent combustion. Because water transport during heating delays branch and foliage drying, it also must influence the height of crown scorch if ignition does not occur.

When wildfire heat emission is severe, approximately 6 J cm^{-2} s^{-1} are incident at the needle surface (R.A. Susott, personal communication). This is 2000 times the rate associated with normal transpiration and 100 times the steady rate of absorption attained in the calorimeter. Thus, it is apparent that the calorimeter replicates heat emission associated with only minimal intensity wildfires. Whether heating-related water transport is sufficient to inhibit combustion during moderate and severe heat intensities can only be inferred, and is likely dependent upon several interacting factors. Two primary factors are undoubtedly the velocity and amount of water transported.

From our studies, it is evident that heating-related water transport by nondrought-stressed lodgepole pine trees to its

branches is rapid. In the calorimeter, where heat intensities were minimal, water loss from intact branch tips immediately intensified relative to water loss from detached tips when heating began. In our potometer study, well-watered lodgepole pine branches went from ambient temperature directly into an oven set at 225 C (Cohen and others 1988). Here, heat intensity was more akin to severe wildfire conditions, and branch water uptake from potometers substantially increased above preheating rates in just over 1 minute. Trees boles and branches may not deliver water as efficiently as potometers. Nonetheless, our studies show a rapid water transport response to heating over a wide range of intensities.

When foliage is heated, vapor pressure deficits at the leaf surface must cause stomata to close tightly. For heating-related water vaporization to occur, stomatal guard cells must deform and/or the leaf cuticle melt, minimizing leaf resistance. After deformation, vapor flow becomes limited by internal plant resistances and water availability. When plants are drought-stressed they do not have enough water available for normal transpiration (Kramer 1983), and must therefore be less capable of transporting water to heated branches. Thus, the amount of water transported in response to heating is probably strongly dependent on plant water stress; internal resistances are normally small (Jensen and others 1961, Neumann and others 1974).

Initial water content of foliated branches is known to be an important regulator of crown fire behavior, but is a poor indicator of plant water stress (Kramer 1983). Therefore, water

content may not be highly correlated to the amount of water transported during heating. Water stress indicators more indicative of plant water stress include water potential and relative water content. In future crown fire studies, water potential and relative water content should be examined for their relationship to crown fire hazard.

CONCLUSIONS

Results of this study indicate that nondrought-stressed lodgepole pine trees transport significant amounts of water to heated foliated branches. Heating-related water transport slows the rate of drying of branches subjected to high heat intensities and must therefore influence crown ignition susceptibility and fire behavior. The degree of plant water stress probably controls the amount of water transported during heating. If the degree of water stress in different plant species can be related to varying amounts of water transported during heating, improved models for crown fire behavior and hazard assessment can be developed.

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Table 1. Mean water content and standard deviation of 3 branch tip samples associated with each of the 18 matched pairs of branch tips heated in the calorimeter. Also shown are the residual water contents of intact branch tips after their removal from the calorimeter. Overall mean water content was 120.8 %. Mean residual water content was 10.8 and 0.0 % for intact and detached branch tips, respectively.

	Water Content (%)		
Pair	Mean	s.d.	Intact Branch Residual
1	147	5.4	17
2	117	7.6	6
3	113	4.6	0
4[a]	126	13.5	14
5	121	2.5	18
6	107	5.1	15
7	118	5.3	15
8	120	2.2	5
9	120	3.5	10
10	108	3.6	10
11	115	2.1	3
12[a]	119	11.7	12
13[a]	126	24.2	12
14[a]	121	10.3	16
15	124	8.2	16
16	135	5.5	2
17	126	2.3	12
18[a]	123	11.8	11

[a] branch pairs that were excluded from calorimeter data analysis because of high s.d.

Figure 1. Mean difference in cumulative energy absorbed per gram dry branch tissue by 13 branch tip pairs (intact minus detached) heated in the calorimeter from ambient temperature to 250 C.

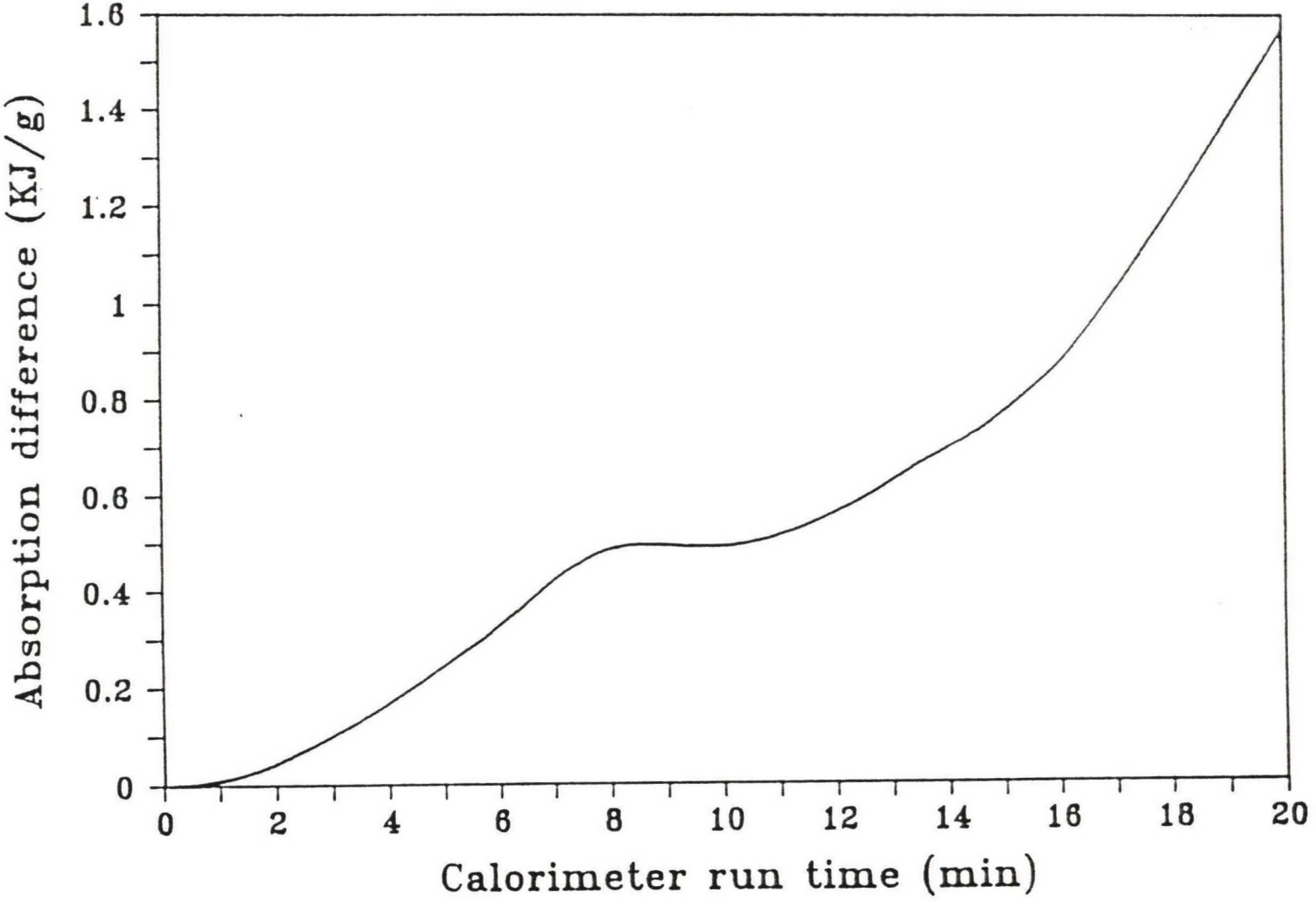
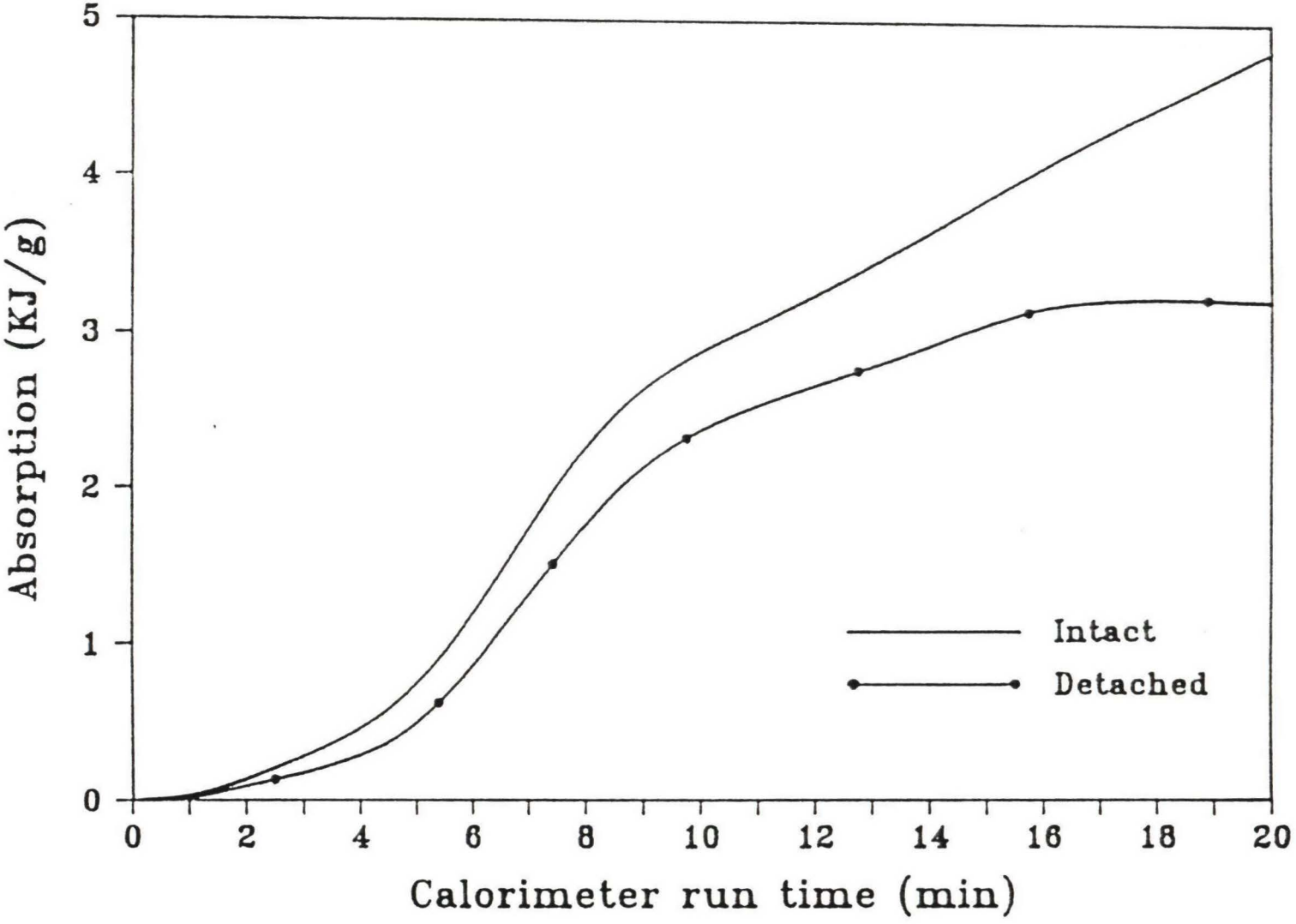

Absorption difference (KJ/g)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
16
18
20
Calorimeter run time (min)

Figure 2. Mean cumulative energy absorbed per gram dry branch tissue by 13 intact and 13 detached branch tips heated in the calorimeter. Data were corrected for blank run energy losses.


Absorption (KJ/g)
0
1
2
3
4
5
0
2
4
6
8
10
12
14
16
18
20
Calorimeter run time (min)
Intact
Detached